High-Throughput Distributed Spacecraft Network: Architecture and Multiple Access Technologies

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Abstract - **BBN Technologies (BBN), under a task for the Space Communications Project, designed the High-Throughput Distributed Spacecraft Network, or Hi-DSN. It provides a self-forming vertically integrated network infrastructure for establishing and maintaining high-throughput multi-hop communications among spacecraft operating in diverse orbits. The Hi-DSN integrates the predictability of orbital movement to establish and maintain cross-links and multi-hop routes, *ad hoc* networking capabilities to autonomously discover "new" neighbors, null-steered spatial multiplexing to maximize re-use of the allocated spectrum, and variable-rate cross-links to maximize network connectivity under large inter-spacecraft distances and distance differentials. The Hi-DSN architecture is hierarchical and can be extended to provide dynamic "terminal affiliation and handoff" for transferring data from spacecraft to aircraft and spacecraft to ground terminals and sensors. The descriptions included in this paper focus on the aspects of the architecture that are relevant for the planet vicinity networks, part of NASA's future space-based internetwork communications infrastructure, and specifically on the enabling physical-layer, medium-access control (MAC) layer and sub-network level (i.e., below IP) technologies required to create a scalable communications infrastructure that can be used to extend the (terrestrial) Internet to space. In a follow-on development for NASA, BBN is designing the architectural extensions and developing the protocols to extend Internet VPNs to space, or SpaceVPNs.**

Keywords: Satellite networks, multi-hop networks, sensor networks, satellite multiple access, variable rate modulation and encoding, *ad hoc* spacecraft networks.

I. INTRODUCTION

NASA's past work in space communications was developed to provide communication services that were specific and optimized to each mission. The nature, communication needs and inter-spacecraft networking requirements of such missions vary broadly, and although the interfaces and protocol used in different missions were standardized, the resulting "ensemble" of different communication systems is not integrated into an overall autonomous communication infrastructure, wherein the in-space nodes can communicate with each other as well as with users on Earth through the Internet [1]. The need of a scalable integrated infrastructure is even more relevant today, when NASA, in response to the President Bush New Vision for Space Exploration Program [2], is reorienting its focus to long-term missions oriented to human missions for exploration of the Moon, Mars and asteroids; human settlements in space; and large in-space observatories.

The need of such an integrated space communications infrastructure, including requirements identification, concept-architecture and related technology developments, has been the object of investigations and workshops [3, 4] at the various NASA centers. Figure 1, from [5], illustrates the main elements of an integrated space communications architecture developed by NASA's Space Communications Project based on needs and requirements of the various NASA enterprises, and in line with the president's new vision for space exploration.

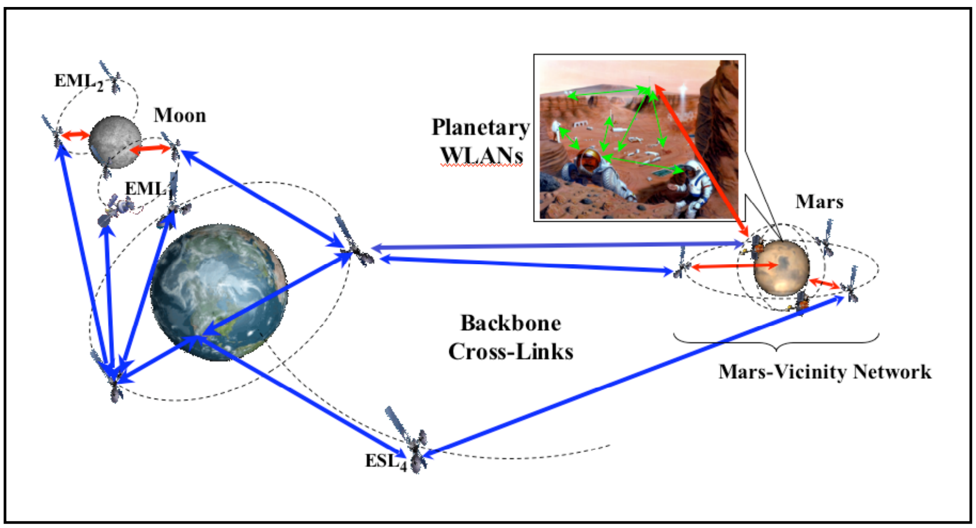

Fig. 1. Integrated space communications infrastructure.

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Very much like the terrestrial Internet, the architecture of the integrated space communications infrastructure is composed collection of networks deployed in the immediate vicinity of a celestial body being observed and/or explored called, generically, <plnet_name>-Vicinity Networks (e.g., Earth, Moon, Mars-Vicinity Networks) linked together through an inter-planetary backbone network that will likely include relay satellites placed in the Earth-Moon Lagrange orbit and in the Earth-Sun Lagrange points L1, L2, L4 and/or L5 to provide high data rate backbone capabilities to deep space observing and science missions. The Mars-Vicinity Network in Figure 1, as an example of a planet-vicinity network, will likely evolve over time to include elements (i.e., surface-based and air-mobile nodes, local and wide area wireless networks, access links, low and medium-altitude orbit satellites, synchronous-orbit relays, etc.) of the communications infrastructure deployed in and around the Earth.

This paper describes the architecture and key physical-layer and medium access control (MAC) layer technologies for a High-Throughput Distributed Spacecraft Network (or Hi-DSN) developed for NASA by BBN that could be used as the basis of future Internet-friendly planet-vicinity networks. The Hi-DSN provides a self-forming vertically integrated network infrastructure for establishing and maintaining high-throughput multi-hop communications among spacecraft operating in diverse orbits. It integrates the predictability of orbital movement to establish and maintain cross-links and multi-hop routes, *ad hoc* networking capabilities to autonomously discover "new" neighbors, spatial multiplexing to maximize re-use of the allocated spectrum, and variable-rate cross-links with multi-code spread spectrum to maximize network connectivity under large inter-spacecraft distances and distance differentials.

Figure 2 illustrates the integration of spatial multiplexing and time-code multiplexing when three (or more) spacecraft transmit to a common target spacecraft.

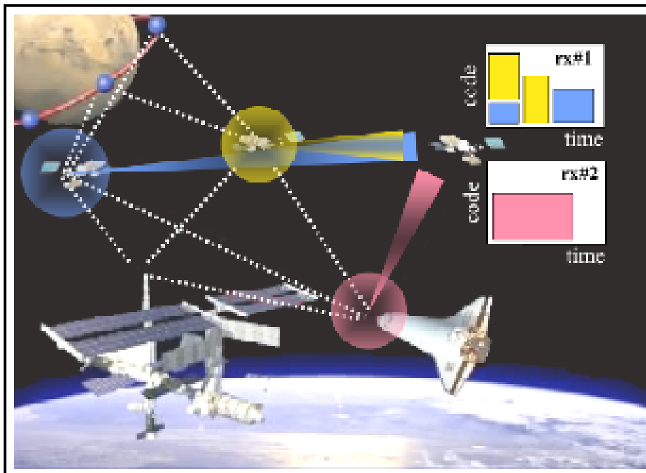

Fig. 2. The integration of spatial and time-code multiplexing enables full re-use of the available spectrum in each cross-link.

Transmission is performed in bursts, with one packet per burst. The spectrum is fully re-usable in the cross-links that are spatially isolated. The spectrum is shared using time and/or time-code multiplexing during the times in which the spacecraft become "aligned." Multi-code multiplexing is used, as described in this paper, to adjust each cross-link data rate to "close the link" between each source-destination spacecraft pair. The inter-spacecraft communication strategy is QoS-aware, and the number of shift-orthogonal codes (described later) used in the encoding of each packet burst is selected to meet bit error rate (BER) and delay/delay-jitter requirements of each *flow* that compose the aggregate packet traffic over each cross-link.

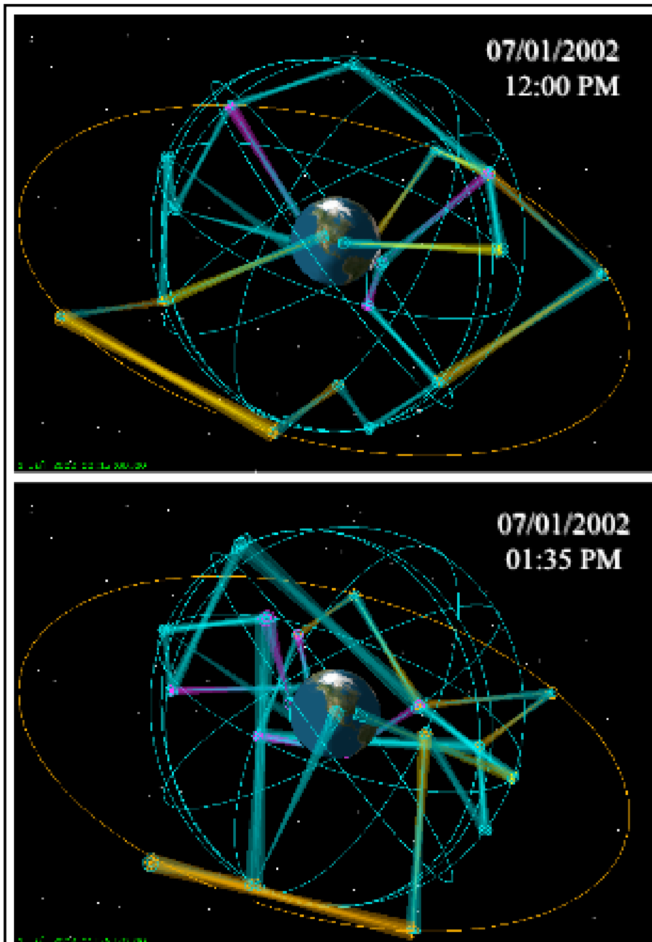

Fig. 3. The number of cross-links and data rate of each cross-link adapts to the changes in the constellation geometry, with the connectivity requirements of each mission.

The number of in-range neighbors per each spacecraft, and the distances and link performance (e.g., signal to noise ratio or SNR) of each of the cross-links change over time with the constellation movement. Figure 3 shows, as an example, snapshots (STK-tool animation of an OPNET simulation) of the geometry and the cross-link connectivity of a typical multi-orbit constellation with spacecraft in LEO, MEO and GEO orbits. In the Hi-DSN system, the transceiver in each spacecraft can establish, ideally, one cross-link per in-range neighbor spacecraft—at the data rate required to close the link—while using a single modem and a single array antenna. This capability is used to control the overall link-level connectivity properties of the network as a whole, including the formation of clusters.

The Hi-DSN architecture is hierarchical and can be extended to both include ground-station *gateways* as integral part of the space-based network and provide dynamic “terminal affiliation and handoff” for transferring data from spacecraft to aircraft and spacecraft to ground terminals and sensors. Figure 4 (from STK-tool animation of an OPNET simulation) illustrates the integration of ground-station gateways in the space-based constellation and the first-time establishment of cross-links (i.e., neighbor discovery) between the gateways and each spacecraft in their field of view.

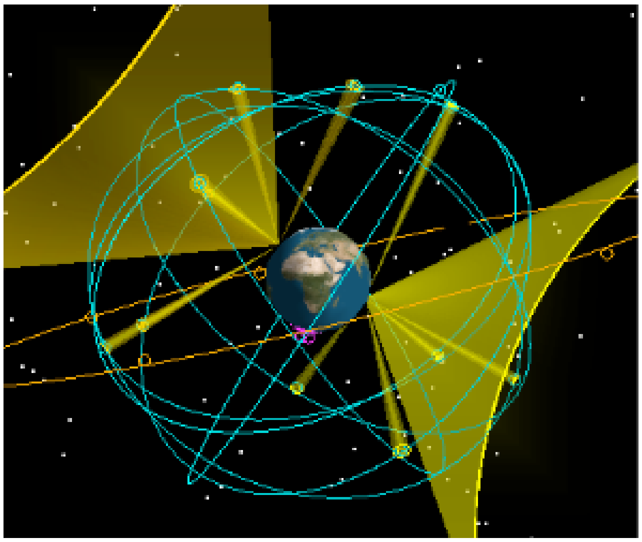

Fig. 4. Ground station gateways can be made integral part of the space-base network and, as the spacecrafts, dynamically find in-range neighbors and establish high-data rate cross-links.

Key aspects of the Hi-DSN architecture in action have been demonstrated using a laboratory prototype and OPNET simulation. The laboratory prototype enabled evaluating how the modulation, encoding, and multiplexing technologies perform under extreme differences of distance (attenuation) and synchronization (frequencies and delays) between space links. The OPNET simulation enabled evaluating how the higher-level protocols scale to large networks.

The descriptions included in this paper focus on the aspects of the architecture that are relevant for the planet vicinity network problem, and on the enabling physical-layer, medium access control (MAC) layer and sub-network level (i.e., below IP) technologies required to create a scalable communications infrastructure that can be used to extend the (terrestrial) Internet to space.

In a follow-on development for NASA, BBN is designing the architectural extensions and developing the protocols to extend Internet VPNs to space, then known as SpaceVPNs.

A. Key Physical and MAC-Layer Challenges

Key challenges addressed in the Hi-DSN architecture (and engineered into the technologies used to implement the network) include:

- Inter-spacecraft connectivity under a wide range of propagation delays, relative velocity — As an example, for spacecraft in low-altitude orbits, the inter-spacecraft distances may range from 100 km to 10,000 km requiring, for connectivity and aggregate throughput maximization, a four-order-of-magnitude control over the data rates (e.g., from 100 Kbit/s to 1 Gbit/s);
- Network self-formation for topologies ranging from few spacecraft in simple flying formation, to large complex and dynamic topologies involving, possibly, aircraft and hundreds of spacecraft in multiple-altitude orbits;
- Spacecraft and network-wide aggregate throughput maximization with multiple-times-over reuse of the allocated spectrum;
- Internetworking between spacecraft with different power-and-aperture communication capabilities;
- *Ad hoc* networking capabilities with full control and, ideally, complete elimination of typical interference that arise in such networks;
- Efficient allocation of communications resources (e.g., power and bandwidth) to multiplexed traffic originated from a possibly arbitrary mix of applications with different QoS (BER, delay, etc.);
- Efficient support for transmission of isolated datagrams and stream traffic packets with minimum transmitter-receiver handshakes and burst scheduling overhead.

In the following subsection, we provide a simplified (and possibly unrealistic) description of a planetary exploration mission involving the deployment of a large spacecraft constellation. Such an example is used, in this paper, solely to exemplify the various topologies that a constellation may assume, the varying nature of the communication requirements as the mission evolves, and to provide initial justification for the use of *ad hoc* networking concepts and techniques for spacecraft networking.

B. Flexible Networking

Deployment of a large spacecraft constellation for planetary exploration (e.g., to Mars) will likely occur in stages and over time. While on their way to the destination planet, they will likely arrange themselves in a *formation-flying* configuration with fixed or minimally varying short distances among them. Depending on the number of spacecraft and deployment specifics, the spacecraft may further arrange themselves in clusters.

As the spacecraft arrive at the destination, they will likely spread and self-arrange themselves into orbits around the planet, possibly at different altitudes. The resulting network, albeit fully deterministic, will exhibit aspects of an *ad hoc* network. This is true during its formation stage and when individual spacecraft do not have pre-stored (or access to) orbital information of ALL other spacecraft in the constellation. Naturally, with the appropriate communication mechanisms in place (as described in this paper), a spacecraft can learn about each other’s orbital parameters, measure relative distances and velocities and even, if needed, re-synchronize their internal clocks to a spacecraft dynamically-selected as reference. In the Hi-DSN, the above initial information gathering and measurements, including the exchange of orbital parameters (when and if available), happen as part of a distributed protocol called *Neighbor Discovery*. A *Distributed Network Synchronization* protocol establishes, over time, of a common time and frequency among all nodes in the constellation.

Over time, the initial deployed constellation around the planet will eventually be augmented by new spacecraft. Newcomer nodes may include spacecraft with specialized sensing capabilities and more powerful (i.e., next generation) communication capabilities and are required to fly at a different altitude orbit. In the Hi-DSN, newcomer nodes are able to integrate themselves into the network with minimal disturbance to the existing constellation, leveraging network adaptation techniques developed for terrestrial *ad hoc* wireless networks.

These newly-arrived spacecraft, together with the already in-place spacecraft, creates a more complex communication environment, where link switchovers occurs very frequently and links with fast varying capacities are the rule, not the exception. The overall system, albeit fully "predictable" over time, becomes almost intractable when one considers the amount of information that needs to be "configured" in ALL spacecraft, and the additional synchronization requirements that would be needed if we were to continue using conventional, scheduled-link switchover technologies as a means to maintain continued connectivity. The Hi-DSN uses an *ad hoc* networking approach, where each spacecraft dynamically "discovers" in-range neighbor spacecraft, dynamically affiliates to neighbor router spacecraft, and dynamically form a three-level hierarchical network.

II. Hi-DSN Technology Summary

The Hi-DSN architecture assumes the use of RF (30 GHz) cross-links and array antennas with null-steered digital beamforming to minimize (and eventually completely eliminate) cross-link interference while maximizing the use (and re-use) of the available spectrum through spatial multiplexing. It also includes support for burst rates varying over four orders of magnitude (i.e., from 100 Kbit/s to approximately 1 Gbit/s) to assure connectivity over wide-range distances, and to provide support for application mix with varying QoS (e.g., different BER and delay/delay jitter characteristics).

The Hi-DSN network infrastructure integrates a number of Physical-Layer, MAC-layer and Sub-Network-Level technologies. These technologies are summarized below.

A. Physical Layer

The Physical Layer is highly optimized for connectivity, power efficiency, and maximum spatial re-use of the available spectrum. It includes mechanisms for:

- *Transmission at Ka-Band*: Enables high data rate transmission and spatial reuse of the available spectrum with small-size, high-gain array antennas.
- *Direct Sampling Down Conversion*: Enables digital beamforming and multiple cross-links per spacecraft with a single modem.
- *Null Steered Burst Transmission*: Enables burst transmissions from one spacecraft to another within-range spacecraft without causing interference to any other spacecraft 'known" to be in the neighborhood of the transmitting node.
- *Null Steered Burst Reception*: Enables a spacecraft to receive without interference from (a) nodes that may be transmitting simultaneously to a common destination node and/or (b) nodes that may be transmitting to different destination nodes.
- *Variable Rate Cross-Links:* Enables spacecraft to maintain connectivity over a wide range of distances by adapting the cross-link data rate (e.g., from 100 Kbit/s to 1 Gbit/s) to the varying link attenuations (e.g., for distances varying from 100 km to 10,000 km);
- Constant-Envelope *Split-Phase Shift Keying Modulation*: Enables efficient use of the available RF power by allowing the operation of the array antenna power amplifiers at or near to saturation.
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B. MAC-Layer

The MAC Layer is highly optimized for spectrum reuse through spatial multiplexing. The MAC-Layer includes:

A *Space-Link Frame* that provides support for space-and-time synchronization (i.e., Direction of Arrival and propagation delay measurements), burst transmission of packet traffic with isolated (isolated datagrams), intermitting (bursty packet traffic) and recurring (stream traffic flow) characteristics, and for the discovery of new neighbors;

A *Channel Access Mechanism* that integrates Spatial-Division, Time-Division and Code-Division Multiple Access leveraging the direct-sequence orthogonal code multiplexing capabilities of BBN's TDMA with CDMA-encoding Multiple Access (TCeMA), described in subsequent sections in this paper;

A QoS-oriented *Bandwidth Allocation Mechanism* that integrates support for long-term bandwidth allocation for rate-based and volume-based application traffic, and for packet flows with different delay and delay-jitter characteristics.

C. Sub-Network Layer

The Sub-Network Layer is highly oriented to maintaining the network connected (i.e., a single "island") and to controlling the connectivity degree (i.e., number of neighbors) in the constellation. It includes:

Neighbor Discovery Protocol: Enables a node to advertise itself, find other nodes, and achieve fame, time-slot and initial frequency synchronization with any other node that that happens to be within range;

Network Synchronization Protocol: Enables each node in the network to, over time, achieve global frame-epoch synchronization while synchronizing its local internal clock and frequency generators to a designated and/or dynamically selected Reference Node.;

Decentralized Routing Protocol: Maintains, at each node, a topology database with information about the active links of each node in the network and determines, for each destination node, the next-hop (or candidate next-hops) to reach a destination;

Node Affiliation Protocol: Enables *endpoint* nodes to find a *router* node that can relay traffic on its behalf, and perform dynamic hand-off as necessary as the network topology and geometry changes over time;

Packet Forwarding Protocol: Makes decisions, when a packet arrives, of what should be done with it (i.e., consume, relay or drop).

III. Types of Nodes

Figure 5 illustrates the topology of the Hi-DSN network. The network (self) organizes itself into a tree-like hierarchy for scalability. The elements that participate in the network are called, generically, *nodes*. Nodes can have different combinations of mobility, routing and transmission characteristics.

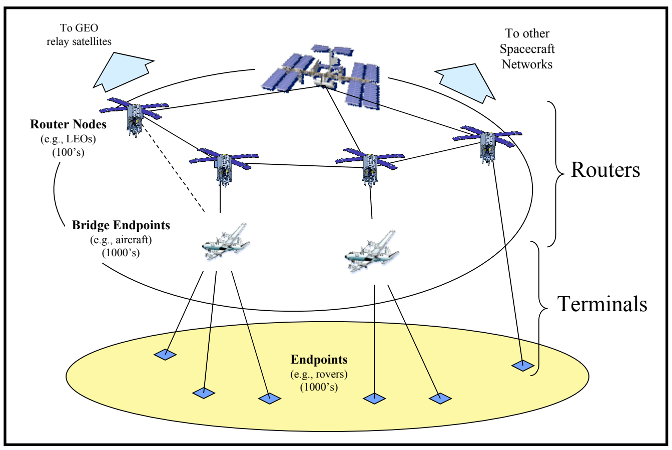

Fig. 5. The Hi-DSN network includes router and endpoint nodes arranged in a three-level hierarchy.

In terms of mobility, nodes are classified, generically, as *in-orbit nodes* (e.g., spacecraft in multiple-altitude LEO, MEO, GEO or elliptical orbits), *air-mobile nodes* (e.g., aircraft and air-mobile sensors), and *ground-based nodes*. *Ground*-based nodes can be further classified into mobile (e.g., robots, exploration rovers) and fixed (e.g., sensor system base station, ground terminal). The relative position and translational movement (i.e., coordinates and velocity of the spacecraft center-gravity) of *in-orbit* and *ground-fixed* nodes, albeit arbitrary, can be accurately predicted over time. The relative position and velocity of air-mobile and surface-mobile nodes have to be "discovered-and-tracked" over time.

Nodes that perform routing functions (e.g., spacecraft in low, medium and planet synchronous orbits), called *router nodes* (or simply *routers*), form a mesh network at the highest level. Nodes that are only sources or destinations of traffic, called *endpoints,* may be affiliated with a router. The endpoints themselves may be arranged in a two-level hierarchy (thereby making a total of potentially three levels) with some endpoints acting as a *bridge endpoint* for others. For instance, an aircraft could act as a bridge for a surface-exploration robot on the surface of the planet.

In what follows, for simplicity, we assume that all *in-orbit nodes* are also *routers.* We also assume that ground-fixed nodes that are used as gateways between the space and ground segments participate in the space-based router constellation by routing traffic between spacecraft. In addition, spacecraft located in advantageous orbit altitudes (e.g., synchronous or high-elliptical orbits) can also function as space-based gateways, routing traffic between the Hi-DSN network and other NASA networks, including NASA's future space internetwork backbone.

IV. Hi-DSN Physical Layer

In the Hi-DSN network, each spacecraft is equipped with a single router, a single transceiver and a single pair of transmit-receive array antennas to achieve low cost. All router nodes have identical Physical-Layer level characteristics (e.g., modulation, FEC, multiplexing, etc.) but can have different RF front-end capabilities (e.g., RF power, and beam gain and agility). Inter-spacecraft cross-links use RF array antenna technology to achieve the required beam agility and Ka-band frequencies to achieve high-directivity with a relatively small profile antenna. They also assume the use of spatially isolated transmit-and -receive array antennas to achieve full re-use of the allocated spectrum in each cross-link. Because of the nearly arbitrary albeit predictable topology, digital beamforming is used to establish a varying number of cross-links per spacecraft. Because of the nearly arbitrary, albeit predictable geometry, antenna null steering is used to minimize interference between cross-links. In addition, because of the large inter-spacecraft distances and, more importantly, because of the typical multiple order of magnitude difference between such distances, a novel BBN-developed multi-code multi-bit modulation-and-encoding [6, 7] is used on each cross-link to achieve bit rates varying over a four-order-of-magnitude range (e.g., from 100 Kbit/s to approximately 1 Gbit/s) to "close the link" to neighbor spacecraft. In order to optimize the use of on-board power, a BBN-developed patent-pending [8] Split-Phase Shift Keying (or SPSK) modulation is used to enable signals transmission at a constant power with the SSPA of each array antenna element operating at or close to saturation. Finally, because of the typical large delays of the inter-spacecraft links, a multiple access strategy that does not require "burst transmission coordination" among neighbor spacecraft was developed.

A. Null-Steered Beamforming

Burst transmission in the in the Hi-DSN system is performed using two types of beams (illustrated in Figure 6):

- **Null-Steered Broadcast:** A transmission performed with antenna nulls toward the directions of ALL in-range nodes known by the transmitting node and, ideally, equal gain in all other directions within the field-of-view of the array antenna;
- **Null-Steered Point-to-Point:** A transmission performed with a single high-gain pencil beam in the direction of a target node, and with antenna nulls pointed towards all other in-range nodes.

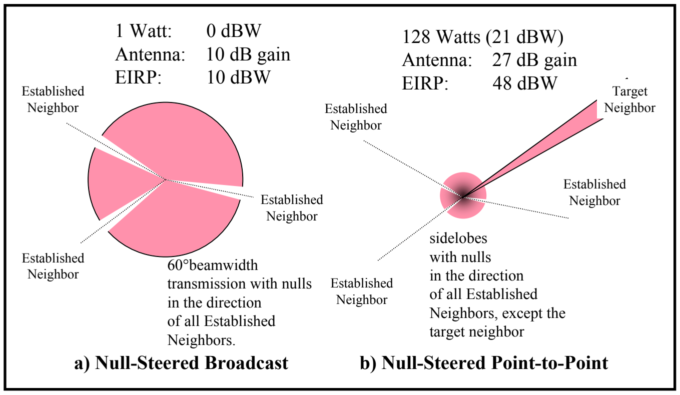

Fig. 6. The systematic use of null-steered beams at both transmission (broadcast and point-to-point) and reception (point-to-point) enables full re-use of the spectrum in each cross-link.

In the Hi-DSN system, burst reception is always performed with a null steered point-to-point beam, in which a maximum-gain receive beam is formed (using digital beamforming techniques) in the direction of a given target node while a antenna null are directed towards the direction of each of the remaining in-range nodes.

The systematic use of null-steering in both transmission and reception "creates" non-interfering cross-links and simplifies the overall physical layer structure of the network: from *"mesh"* to a collection of *"independent stars."* It also dramatically reduces the need for *"hand-shakes"* between transmitter-receiver pairs (very costly over long-delay space links), enabling a transmitter to simply *point and shoot* to a selected target node whenever it has a packet destined to that node.

A. Data Rates and Beam Agility

Table 1 illustrates typical distances (minimum and maximum) in a example constellation with 21, 12, 12 and 7 spacecraft placed respectively in LEO , MEO, GPS and GEO-altitude orbits set respectively to approximately 820, 9600, 20000 and 36000 kilometers. Table 2 illustrates the corresponding data rates of Hi-DSN cross-links established over such distances assuming 30 GHz, 100 Watt transmitters, E_S/N_0=10 dB, multi-bit modulation (when possible), and antenna diameters set respectively to 25 cm, 30 cm and 50 cm for the LEO spacecraft, MEO and GPS-altitude spacecraft, and GEO spacecraft and ground terminals.

TABLE 1
EXAMPLE OF MINIMUM/MAXIMUM INTER-SPACECRAFT DISTANCES (IN KM)

TO / FROM	ES	LEO	MEO	GPS	GEO
ES	MIN / MAX	820 / 5330	9560 / 13900	20230 / 24500	35860 / 40100
LEO	820 / 5300	350 / 6490	8740 / 17830	19400 / 29060	35030 / 44990
MEO	9560 / 13900	8740 / 17830	1390 / 29170	10660 / 40400	26290 / 56330
GPS	20230 / 24500	19400 / 29060	10660 / 40400	2320 / 51630	15630 / 67560
GEO	35860 / 40100	35030 / 44990	26290 / 56330	15630 / 67560	36650 / 83480

TABLE 2
EXAMPLE OF MINIMUM/MAXIMUM CROSS-LINK DATA RATES (IN BIT/S)

TO / FROM	ES	LEO	MEO	GPS	GEO
ES	MAX / MIN	7.4 x10^8 / 2.1 x10^8	9.3 x10^7 / 4.4 x10^7	2.1 x10^7 / 1.4 x10^7	1.8 x10^7 / 1.5 x10^7
LEO	7.4 x10^8 / 2.1x10^8	7.4 x10^8 / 3.5 x10^7	2.8x10^7 / 6.6 x10^7	5.6 x10^6 / 2.4 x10^6	4.8 x10^6 / 2.8 x10^6
MEO	9.3 x10^7 / 4.4x10^7	2.8 x10^7 / 6.7 x10^6	7.4x10^8 / 3.5 x10^6	2.7 x10^7 / 1.8 x10^6	1.2 x10^7 / 2.6 x10^6
GPS	2.1x10^7 / 1.4 x10^7	5.6 x10^6 / 2.4 x10^6	2.7 x10^7 / 1.8 x10^6	5.7 x10^8 / 1.1 x10^6	3.5 x10^7 / 1.8 x10^6
GEO	1.8 x10^7 / 1.5 x10^7	4.8x10^6 / 2.8 x10^6	1.3 x10^7 / 2.6 x10^6	3.5 x10^7 / 1.8 x10^6	1.7x10^7 / 3.3x10^6

Key requirements related to beam agility and cross-link data rate (that became capabilities of the implemented Hi-DSN architecture) include:

- Independent transmit-direction and receive-direction array antennas with different power, beamforming and beam agility characteristics to achieve full duplex links and maximize network flexibility.
- One-at-a-time burst transmission with maximum power (i.e., saturated power amplifiers), o achieve power efficiency over, typically, power-limited cross-links.
- Beam agility in elevation and azimuth (with null steering) to achieve non-interfering cross-links with multiple neighbors.
- Beam agility in beamwidth (i.e., beam directivity or gain) to facilitate the "discovery" of neighbor nodes, especially air-mobile routers and ground-based endpoints.
- Transmission at bit rates over four orders-of-magnitude (e.g., from 100 Kbit/s to gigabit per second rates) to close the links with neighbor spacecraft located at varying distances.

- Transmission at a system fixed symbol rate to allow a spacecraft to receive simultaneously from multiple neighbors with fixed transceiver front end (i.e., fixed receive -filter bandwidth).
- Space –to-time multiplexing "handoff" to accommodate situations in which spacecraft become spatially aligned.

B. Integrated Spatial, Time, and Code Multiplexing

Figure 7 illustrates the encoding and multiplexing strategy employed in the Hi-DSN system. Spectrum sharing and re-use is achieved through multiplexing performed in four different domains: frequency (multiple carriers—not shown), spatial (multiple beams), time (frame with multiple time slots), and code (multiple simultaneous transmissions per time slot using shift-orthogonal direct-sequence spread spectrum signals). The technology used for time-code multiplexing, called Tdma with Cdma-encoding Multiple Access (or TCeMA) has been extensively tested and is described in [6-8].

In the Hi-DSN's TCeMA we differentiate between *channel symbol rate* and cross-link *effective symbol rate*. The channel symbol rate is fixed to facilitate the implementation of filters at the transmitter and receiver, the overall synchronization at the frame-epoch, symbol-time and carrier-frequency levels and, more importantly, to enable any given node to receive simultaneously from multiple neighbors at different effective symbol rates, each selected to "close the link" with each neighbor, and to achieve the BER of each application flow. With the multi-code encoding of TCeMA, the effective symbol rate of a burst— proportional to the fraction of the total number of codes used—can vary from cross-link to cross-link, from burst to burst within each cross-link, and it can be different for the preamble and payload areas of each burst. This latter capability is required for QoS-responsiveness and/or whenever one wants to control the power and bandwidth resources allocated to each application traffic flow over a "trunk" carrying multiplexed traffic from different applications (e.g., sensor data, multi-media voice and video data, and TT&C constellation control data). In the Hi-DSN, as an example, for a channel symbol rate fixed at 100 Msymbol/s (actually 92.16 Msymbol/s), 1000 (actually 1024) shift-orthogonal codes, and BPSK modulation (1 bit/symbol), each code corresponds to 100 Kbit/s (actually 90 Kbit/s) of quantum throughput—the Hi-DSN data rate quantum.

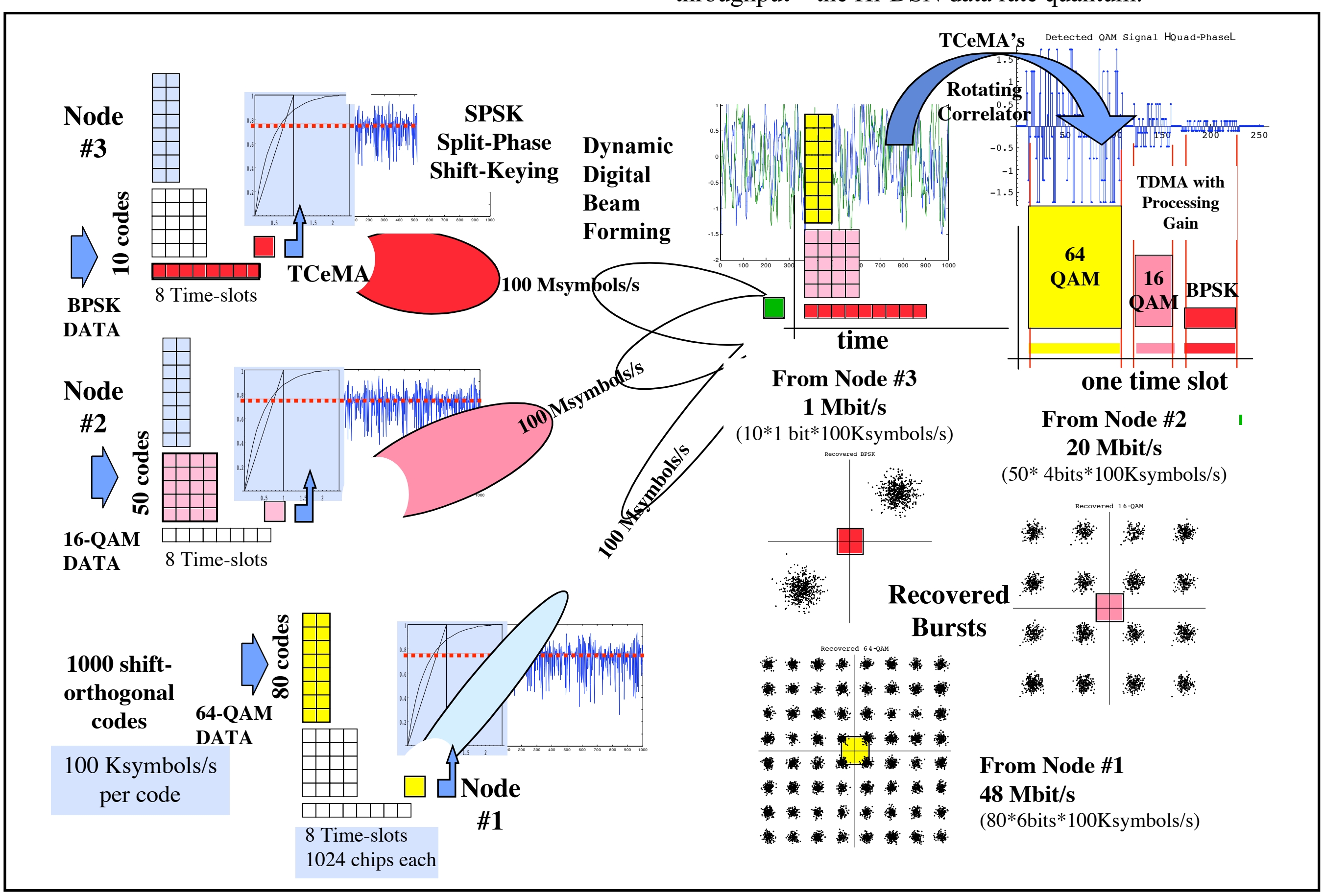

Fig. 7. With TCeMA, a spacecraft can receive simultaneously from multiple neighbors at difference effective symbol rates while using different amplitude-and-phase modulation (e.g., from BPSK up to 256-QAM) in each cross-link.

The use of 10 codes (top link in the figure) would result in an effective symbol rate of 1.0 Msymbol/s (actually 900 Kbit/s). With TCeMA, each transmitter can independently select the modulation level (i.e., bits per symbol), and/or the actual modulation type (M-ary PSK or M-ary QAM, with coherent or differential encoding) used in each burst without causing cross-correlation interference under arbitrary—but bounded—differential delays (up to ±64 channel symbol times) between the various cross-links. In the Hi-DSN system, bursts transmitted to the overhead area of the frame (described in this paper) are transmitted with DPSK modulation, while bursts transmitted to the "data areas" of the frame are transmitted with coherent M-ary QAM modulation, with up to 8 bits per QAM symbol. An additional optimization introduced in the Hi-DSN system, was the engineering of the bursts such that the number of codes per burst and number of bits per symbol and the modulation type used in each burst are informed in the burrs preamble, minimizing otherwise very costly burst-by-burst hand-shakes over the long delays of space-distance links. In Figure 7, we also illustrate the effective symbol and bit rates achieved on the other two example cross-links, with 50 codes and 16-QAM modulation (20 Mbit/s), and with 80 codes and 64-QAM (48 Mbit/s). With TCeMA, for short-distance spatially isolated cross-links, it is possible to use all 1000 codes and, possibly eight bits per symbol, for an effective symbol rate of 100 Msymbol/s (actually 92.16 Msymbol/s) and an effective bit rate of 800 Mbit/s (actually 737.28 Mbit/s).

With TCeMA, the orthogonal codes are obtained as cyclic shifts of a base sequence, where each cyclic shift provides a different direct-sequence spreading code. Signal separation and detection at the receiver is performed through a rotating correlator—efficiently implemented using fast Fourier techniques—that compares the received aggregate signal each cyclic-shift of the same base sequence conjugated (i.e., auto-correlation).

When the rotating correlator rotates—for visualization purposes— at a rate of one cyclic-shift per channel symbol time, the resulting output signal is an exact replica of an equivalent TDMA multiplexed signal—with number of codes per TCeMA-encoded burst made equal to number of time-slots per TDMA burst— *but with a processing gain* inversely proportional to the number of codes used in each burst. The TDMA nature of the signal at the output of the rotating correlator is illustrated by the three consecutive bursts in the upper right side of the figure. The different processing gains—proportional to the fraction of the total number of codes used in each burst—are illustrated by the different amplitudes of the corresponding bursts. The waveform equivalence between the TDMA and TCeMA signals (after the rotating correlator) is illustrated by the "guard-times" between the bursts (identical to the number of codes left unused between the codes allocated to each transmitter), and by the TDMA-identical symbol constellations and eye diagrams (not shown) of each detected burst (illustrated in the bottom-right portion are of the figure).

It is also important to note, that with TCeMA, when different transmissions are performed using distinct codes of the same code family, the separation of the signals at the receiver is achieved independently of the relative received powers, antenna beam gains, spatial overlap, or antenna sidelobe "leaks" that may exist among the receive-beams. In the Hi-DSN system, this last property is used every frame, independently by each spacecraft, to measure and decide about the actual spatial separation between cross-links terminating at any given spacecraft. When the cross-links are deemed as being "not spatially separable" the MAC layer initiates a spatial-to-code multiplexing switchover.

Also with TCeMA, as it will become apparent later, the signals received from different spacecraft DO NOT need to be perfectly synchronized with each other. The synchronization requirements for TCeMA are similar to the synchronization requirements of TDMA, with time uncertainties ranging, typically, from a couple to tens of channel symbol times. This property represents a clear advantage over conventional direct-sequence spread spectrum CDMA techniques used in terrestrial wireless networks (e.g., using Walsh sequences or maximal-length sequences) that require very tight synchronization, typically within a fraction of a chip-time.

In a spacecraft network, the required beam gains (and associated beam beamwidth), and the relative beam directions change continuously with the constellation movement. When the spacecraft are not aligned and there is "enough" spatial isolation (e.g., when the main lobes of the various beams do not overlap), the whole bandwidth (i.e., all spreading codes) is available to each of the beams in each direction (i.e. the available spectrum can be fully re-used). For this, each spacecraft continuously monitors the inter-beam interference (i.e., main lobe overlaps and/or signals that "leak" through the sidelobes) and dynamically "switch" from full-bandwidth/up-to-all-codes per cross-link to shared-bandwidth/shared-codes among the possibly interfering cross-links. Switching from full to shared-bandwidth may cause sudden step-changes in the throughput available in each cross-link. In the Hi-DSN system, the tracking of the relative beam directions, measuring of the isolation among the incident signals (after they been processed for spatial separation and processing gain), and the performing the required code and capacity re-allocations while taking into account the QoS characteristics of the application traffic in each of the cross-links, are integral part of the MAC-Layer protocol.

C. Constant Envelope Burst Transmission

TCeMA uses multi-codes to adapt the effective symbol rate over each cross-link and variable envelope multiple-bit modulation (from BPSK up to 256 QAM) to achieve high throughput over short-range links). Transmission of such signals directly over the channel, due to the typical high peak-to-average power ratios inherent of such multi-code/multi-bit encoding and modulation would require operating the antenna array solid state power amplifiers (SSPAs) at a high input-output backoff, being subject to the resulting penalties on the achievable range and data rates, and costs associated to operating the transceivers in the linear region.

Fortunately, the above problem is not unique to spacecraft networking, and BBN has already developed a patent pending practical solution for it in the form novel modulation overlay (i.e., applied "on top of" other modulations) called Split Phase Shift Keying (or SPSK).

SPSK is a very powerful modulation technique that allows ANY non-constant envelope signal (e.g., M-ary PAM, M-ary QAM, FDMA, OFDMA, multi-code CDMA, TCeMA, etc.) to be transformed into a before-transmit-filter constant power envelope signal and, more importantly, into an after-transmit-filter signal with nearly constant power envelope (i.e., with envelope fluctuation performance comparable to offset-QPSK). The typical point of operation of an SSPA with a typical AM-AM characteristic function, driven by a SPSK modulated signal, is 1 dB of output power backoff.

Another very important property unique to SPSK, is that the demodulation fully restores the modulating signal, including the effects of channel delay, multi-path reflection and filtering operations. Another very important property of SPSK is that most—if not all—of the complexity is at the modulation side, enabling the implementation of cost-effective receivers .

In Figure 7, for each transmitting spacecraft, we illustrate the envelope of the corresponding multi-code/multi-bit SPSK-modulated signals at the output of power amplifiers with typical AM-AM power amplification characteristic. Specifically, the waveforms shown illustrate typical TCeMA-encoding and SPSK overlay-modulation with 3 dB input backoff and 1 dB output backoff, followed by filtering with raised-cosine transmitter filters with 0.3 roll-off factor and 3 dB bandwidth nominally equal to the channel symbol rate.

Another important characteristic of SPSK for space applications, that can potentially facilitate the design and/or reduce the cost of the power amplification devices, result from the fact that the resulting filtered signals have limited dynamic range: just 7 dB worst case in the examples shown, less than 10 dB in general, and practically never reaching zero (i.e., no zero crossings at baseband).

Also in the figure, at the receiving node, we illustrate the amplitudes of the in-phase (blue) and quadrature-phase (green) components of the aggregate signal received, the TDMA-equivalent (but with processing gain) signals separated in time at the output of the rotating correlator, and the corresponding I-Q constellation plots of the detected TCeMA signals (under Gaussian noise) detected from each of the transmitting spacecraft.

It's important to notice that a cross-interference-free signal demultiplexing at the receiving end requires the transmitted signals to be pre-equalized for the SSPA AM-AM and AM-PM (not shown) non-linearity. In the case of SPSK modulation, the required pre-equalization is further simplified by the reduced peak-to-average characteristic of the SPSK-modulated signal.

V. Hi-DSN MAC-Layer

The Hi-DSN Media Access Control (Hi-DSN-MAC) Layer, as the name entails, controls the access and the use of the shared media (i.e., the space) among multiple spacecraft that compose the Hi-DSN system. For this, the Hi-DSN-MAC integrates controls of three multiplexing technologies—spatial multiplexing, time multiplexing and multi-orthogonal-code multiplexing—with network self-formation mechanisms that include a neighbor discovery protocol and controls for accessing and performing near-optimum utilization of the capacity in each or the dynamically established RF cross-link. In steady-state, at the physical and link levels, the Hi-DSN network "behaves" and functions as multiple independent "star-networks," in which each node is the center of its "own" star and the "master" for synchronization and capacity-resource allocation to its neighbor nodes. Each node, by itself, form the transmitting perspective, may participate in multiple "stars." The Hi-DSN MAC-Layer includes a receiver-directed burst synchronization transmission strategy (describe later in this paper) that enables each transmitting node to select the actual transmit times of its bursts (and the actual instantaneous data rates) to different destination nodes without requiring "negotiating" with the corresponding receiving nodes. This capability has been shown, through simulation, to greatly reduce otherwise inherent latency of stream-traffic packet transmission over long delay links.

Characterizations and examples of the above multiplexing mechanisms are provided in the following paragraphs. The frame structure, neighbor discovery mechanisms and burst transmission synchronization are described in follow-on sections.

Spatial Multiplexing creates non-interfering, spatially disjoint physical links between pairs of spacecraft by dynamically beam-forming high-gain antenna beams each other while generating antenna nulls toward all other known neighbors (i.e., Established Neighbors) of each spacecraft.

Time Multiplexing is used mainly to separate interfering signals that cannot otherwise be isolated from each other solely through spatial multiplexing, either because the interfering signals are originated at spacecraft that are spatially-aligned or because the interference happens as a result of inherent uncertainties and/or imperfections in the null-steering implementation.

Multi-Orthogonal-Code Multiplexing performs two functions: (1) implementing the variable transmission rates in each of the spatially multiplexed (or time-multiplexed) links and (2) multiplexing signals from spatially aligned spacecraft that are transmitted intentionally (and simultaneously) toward a common spacecraft (e.g., for spatial/temporal synchronization purposes).

The **Hi-DSN Frame** is common to all nodes and includes control channels that, although dynamically allocated, are (or better become) dedicated to each of its neighbors.

In what follows, we provide a brief description of the above multiplexing techniques. In the next subsection, we review the frame structure and burst composition. The control mechanisms for controlling the access and the use of the shared space (i.e., the MAC-Layer) are described in follow-on subsections.

A. Spatial Multiplexing

Figure 8 illustrates examples of network topology with and without spatially aligned spacecraft.

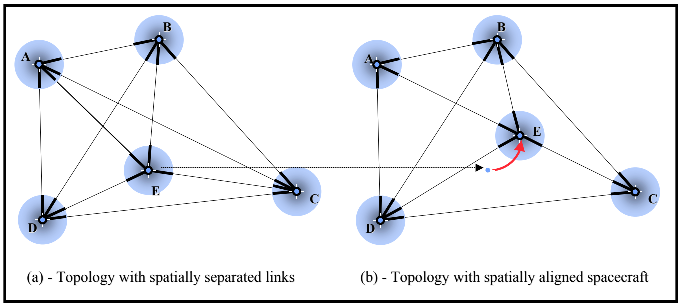

Fig. 8. Example of topologies with spatially separated and spatially aligned cross-links.

In Figure 8a, all links between spacecraft pairs are spatially isolated from each other and hence can coexist simultaneously regardless of burst overlaps in time (if null-steering toward non-target nodes, as described in the paper is consistently applied both at burst transmission and reception). Spatial isolation is enforced by the systematic use of null steering toward all known (but one) neighbor node every time a burst is either transmitted or received. Null steering performed at burst transmission time has the main objective of minimizing the interference toward non-targeted nodes that are within reach. Null steering at burst reception, performed by "placing a null" towards all known neighbor nodes but one, further reduces the possibility of interference. Null steering, due mainly to the fact that the spacecraft are in constant relative movement, is not perfect and interference may still happen. In the figure, as an example, interference may happen when a signal transmitted toward a specific spacecraft (e.g., from A to E) "leaks" and is received by e.g. spacecraft B due to a less-than-perfect transmit null steering towards B and a less-than-perfect receive-null-steering towards A when B is trying to receive a burst from any of the other spacecraft (B, C, D or E). The Hi-DSN system includes mechanisms to check for the actual performance of the null steering process every frame, by alternatively processing the aggregate signal received in the SYNC time slot with both code demultiplexing and spatial demultiplexing, and by checking for any "leftover" power of a signals being (or trying to be) nullified.

Figure 8b illustrates a configuration where spacecraft A, E and C become spatially aligned. A situation that may happen is a transmission from **A** to **E** being performed simultaneously with a transmission from **E** to **C**, and with a transmission from **C** to **E**. The signals from **A** and **C** can be easily separated at **E** through spatial demultiplexing. The signal from **A** destined to **E** will, eventually, be received at **C** in misalignment with the **C** time-slots (i.e., differential delay greater than ±64 channel symbols) creating an opportunity for interference. **C** cannot separate the interfering signals received from A, from the signal destined to **C** but received by **E**, using just spatial demultiplexing mechanisms because the receive beam pointed to **E** also includes **A**. In addition, the intentional signal from **E** cannot be separated from the interfering signal from **A** using solely through code multiplexing.

B. Time-Multiplexing

The only way for node **C** to separate the intentional-signal received from **E** from the non-intentional interference signal received from **A**, is through time-multiplexing: by enforcing that signals from **A** to **E** or **C** do not overlap in time with signals from **E** to **C**. Figure 9 illustrates such a time multiplexing strategy.

In the HI-DSN system we integrate time multiplexing negotiations at the MAC layer to determine the fractions of a frame, frame of the of the multi-frame (or combinations thereof) when node **C** should not receive from either nodes **A** or **E**, as illustrated in Figure 9.

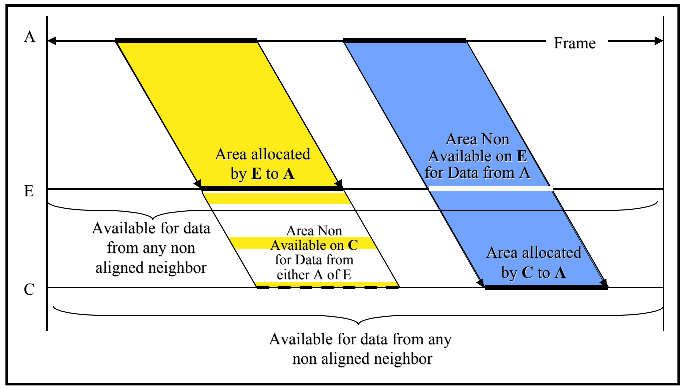

Fig. 9. The MAC protocol includes continuous tracking of the relative spatial alignment, and time multiplexing negotiation among the aligned nodes to work around non-intentional interference.

C. Code Multiplexing

In the Hi-DSN, code multiplexing is implemented using the BBN-developed TDMA with CDMA-encoding Multiple Access (TCeMA). TCeMA assumes the existence of a frame structure and transmission performed synchronized to its time-slots within the allowed time-uncertainty (i.e., ±64 channel symbols). The TCeMA technique is describe in [6-8, 11]. The Hi-DSN frame structure is summarized in the next section.

D. Hi-DSN Frame Structure

D.1 Multi-Frame Structure

The Hi-DSN Frame System is organized in multi-frames, each composed of a fixed number of frames.

The Hi-DSN multi-frame (Figure 10) is composed of frames, 10 milliseconds each. The number of frames per multi-frame can very form "star-to-star" and is set initially to 10 (default value) corresponding to a multi-frame length of 100 milliseconds. The number of frames per multi-frame can change dynamically, under the control of the MAC-Layer, as function of the number of neighbors and aggregate traffic mix.

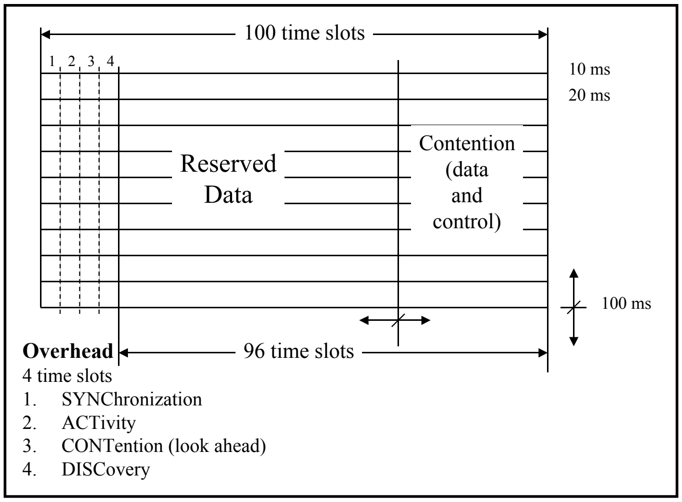

Fig. 10. The HI-DSN Multi-Frame length can vary from spacecraft to spacecraft to accommodate varying number of neighbors, varying-size time-slot pools for contention traffic and varying recurring allocation of time slots for traffic with stream-like characteristics.

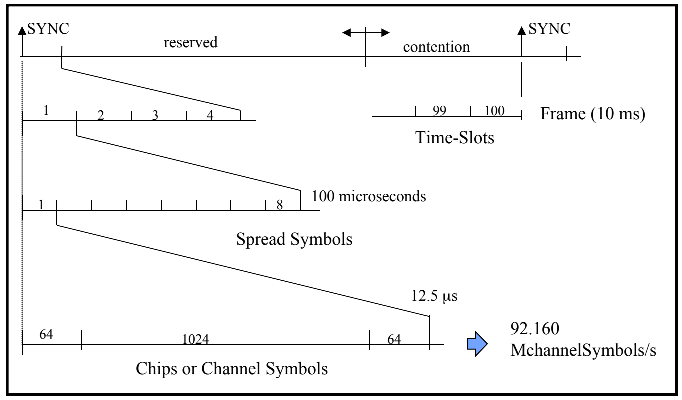

Fig. 11. The HI-DSN Frame capacity is used, mostly, for data (96%), can be arbitrarily partitioned in capacity areas for stream and bursty traffic, and includes a low-overhead area (4%) for synchronization and burst transmission control.

The multi-frame, as well as each individual frame, is divided in two areas: overhead and data. The "data" area is further divided in two sub-areas: reserved data traffic (RESERVED) and contention data traffic (CONTENTION). The boundary between the *RESERVED* and the *CONTENTION* is common across the entire multi-frame, and may vary from node to node (i.e., from "star-to-star").

The overhead area include four time-slots, each dedicated to specific a function:

- **SYNC**hronization time-slots are used for temporal and spatial synchronization of neighbor nodes;
- **ACT**ivity time-slots are used to inform the presence of a burst (in the frame) and its instantaneous effective symbol rate (that can vary from packet to packet) for traffic transmitted in the "reserved data" sub-area of the frame;
- **CONT**ention time-slots are used to inform the presence of a burst and the relative time-code slot position (relatively to the beginning of the CONTENTION sub-area of the frame) for bursts transmitted using slotted-aloha techniques;
- **DISC**overy time-slots are used to listen to HELLO and FOUND_YOU bursts transmitted as part of the neighbor discovery protocol, described later in this paper.

The overhead time slots, in particular the SYNC time-slot, play a crucial role in the synchronization operations performed by the MAC Layer.

D.2. Detailed Frame Structure

Figure 11 illustrates the detailed structure of each frame. The frame length is 10 milliseconds, divided in 100 time-slots of 100 microseconds each. Each time-slot is further subdivided in eight spread-symbol time-slots of 12.5 microseconds each.

Each spread-symbol time-slot corresponds to 1152 channel-symbols: 1024 for the actual TCeMA encoded signal and 64+64 for the left and right cyclic padding, required for code orthogonality even under a worst case synchronization uncertainty.

D.3. Packet Data Encapsulation

In the HI-DSN system, transmission is performed in packets. Packets can have an arbitrary length (in bits). Packets queued to be transmitted are encapsulated as illustrated in Figure 12. Packets are segmented in fixed-length chunks; chunks are FEC protected in turbo chunks; turbo chunks are M-ary QAM modulated, and compressed, into possibly fewer modulated chunks; modulated chunks are packed into fixed-size payloads; payloads are transmitted in containers formed by pre-pending a fixed-size BPSK header to each payload.

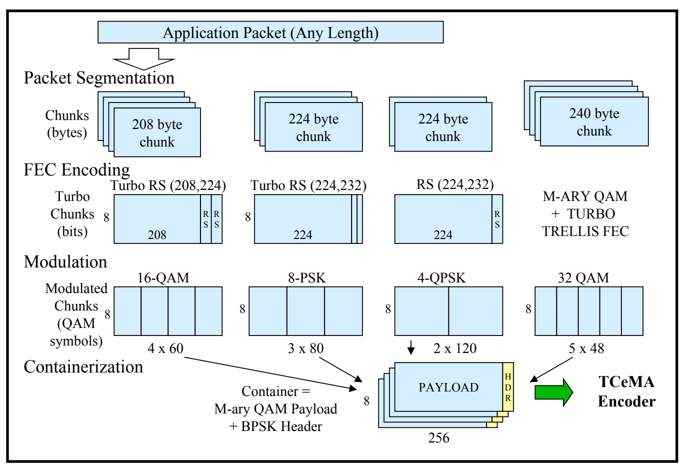

Fig. 12. Packets can be transmitted using a variety of modulation levels, but are always "carried" in fixed-size payloads of 1920 QAM-symbol each.

The payload size is fixed and dimensioned to carry exactly eight 1920 M-ary QAM symbols. Distinct packets are carried in distinct payloads. The modulation level (i.e., bits/symbol) is selected on a per packet basis and, consequently, there is no "mix" of modulation levels in a payload. The modulation level used in the payload is specified in the container header. The number of modulated chunks that "fit" in one payload varies with the modulation level selected for the packet.

D.4. *Frame Loading*

Figure 13 illustrates the relationship between the Hi-DSN frame with the payload, and the container sizes defined in the previous sub-section.

With TCeMA encoding and codes that are 1024 chips long, each spread-time-slot can be used for up to 1024 M-ary QAM symbols. With a code stripe with eight codes, each spread-time-slot carries exactly eight M-ary QAM symbols.

A payload has exactly 1920 M-ary QAM symbols. The container header has exactly 128 BPSK symbols. A full container fits exactly, as shown in Figure 13, in 32 time-slots, where each time-slot is composed of spread-time-slots, each spread time-slot with 1152 channel symbols. With eight codes, each frame carries exactly three containers.

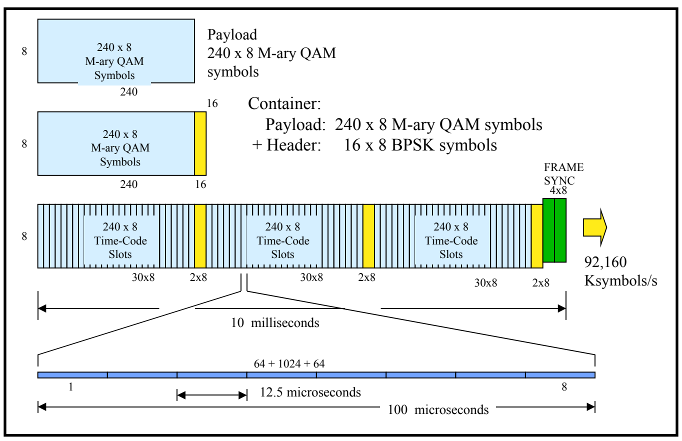

Fig. 13. The DSN frame and the container structures were designed such that a full container (header and payload), when encoded using eight consecutive shift-orthogonal codes, fits exactly in one frame.

D.5. *Frame Throughput*

The number of M-ary QAM symbols can be transmitted per frame and the overall frame efficiency varies as a function the number of codes and modulation levels (i.e., number of bits per M-ary QAM symbol) used.

Transmission in the Hi-DSN system is always performed at the Hi-DSN nominal symbol rate of 92.160 Msymbol/s. The frame load shown in Figure 13 corresponds to one user transmitting three containers per frame using eight codes. The net user-available throughput in this case (in M-ary QAM symbols/s) is 576 Ksymbol/s.

The aggregate multiplexed throughput of the Hi-DSN frame cross-link varies with the number of nodes transmitting simultaneously, number of spatially separable beams, modulation level (i.e., bits per symbol) used by each transmitter, and number of guard codes (i.e., codes left unused between adjacent code-stripes, and needed to accommodate timing synchronization uncertainties in code-multiplexed cross-links transmissions (i.e., when the beams cannot be fully isolated from each other through spatial multiplexing).

The effective throughput per spatially separable beam using 720 codes and BPSK modulation is 51,840 Mbit/s—equivalent to an OC-1 optical link. The effective throughput achievable per beam with BPSK modulation and including the remaining 240 codes is 69.12 Mbit/s. The corresponding cross-link net throughput per beam with 256-QAM modulation is 552.96 Mbit/s—a throughput comparable to a "raw" OC-12 optical link.

VII. HI-DSN MAC FUNCTIONS

The Media-Access Control (MAC) capability for the Hi-DSN system includes four key functions:

- Neighbor Discovery
- Spatial-Temporal Synchronization
- Spatial Multiplexing Control
- Cross-Link Level Control
- Receiver-Direct Burst Synchronization

Neighbor Discovery "finds" a new or re-occurring neighbor and performs rough measurements of the relative spatial direction, frame-time alignment and carrier frequency-synchronization. Neighbor discovery is performed by receiving HELLO and FOUND_YOU bursts in the DISC time-slot. Neighbor Discovery includes the exchange of at least one SYNC bursts with the new or re-discovered neighbor.

The Spatial-Temporal Synchronization function maintains the spatial and the frame alignment of each node to each of its neighbors. This is done by: (1) transmitting and receiving a SYNC burst at least once per multi-frame per neighbor; (2) measuring the direction of arrival (DOA) and time alignment of each SYNC burst received, and (3) providing feed-back of the differential timing error in a return SYNC burst.

The Spatial Multiplexing Control function monitors the alignment between neighbors and "negotiates" with each of the "aligned" neighbor the time-code allocations and time-only allocations required to create non-interfering cross-links.

Every time a data burst is received, the transceiver performs measurements of the link performance (e.g., received power level, SNR, etc.) and of the relative frequency and fine time alignment leveraging the cyclo-stationary properties of the TCeMA-encoded signals. The Cross Link Level Control function uses these measurements to monitor the quality of the cross-link, to define the achievable throughput as a function of the bit error rate and, ultimately, to set the effective symbol rates and modulation levels that can be used over each of the cross-links as a function of the link BER and packet error rates for the various FEC encoding methods.

The Receiver-Directed Burst Synchronization function is responsible for scheduling the transmission of bursts at each node to different neighbors such that, at the transmitter, they don't overlap at the transmitter, and the burst is received time-aligned with the time-slots and carrier frequency at the target receiver. This function includes the estimating and tracking of relative inter-spacecraft movement and the compensating—at transmission—of eventual frequency shifts due to the relative velocity between the spacecraft (i.e., Doppler effect).

These MAC functions are relatively "involved," and in the following sub-sections, we limit the descriptions to a summarized version of the neighbor discovery and the receiver-directed burst synchronization functions.

A. Neighbor Discovery

In the HI-DSN system, we distinguish between two types of neighbors: new and re-occurring. A "new neighbor" is one for which the node performing Neighbor Discovery has no a priori knowledge of relative coordinates and velocity, nor it knows how to perform transmissions that are time and/or frequency synchronized with the neighbor's frame and carrier frequency. A 're-occurring neighbor' is one for which some—or all—of the above information (e.g., from orbital equations)—is already available, and is used to performing transmissions that are spatially directed to the neighbor location, time-synchronized with the selected neighbor frame (DISC time-slot in the overhead area of the frame), and frequency synchronized with the local carrier frequency of the neighbor's transceiver.

A node *supports* its own discovery by an eventual "new neighbor" by transmitting HELLO bursts that scan the whole frame in time-slot steps. Initially, when the node has no known neighbors (called Established Neighbors), these HELLO bursts are transmitted as a sequence of *omni-gain (or FOV-wide) broadcast bursts*. Over time, as the node 'acquires' more and more Established Neighbors, the HELLO bursts are transmitted with *null-steered omni-gain broadcast bursts* (i.e., with an antenna beam with ideally equal gain in all directions and with nulls towards all Established Neighbors).

A node *supports* its re-discovery by a "re-occurring neighbor" by transmitting a HELLO burst with the maximum possible gain towards the re-occurring neighbor, and/or as time-synchronized as possible with start of the DISC time-slot at the re-occurring neighbor, and/or as frequency-synchronized as possible with the carrier frequency at the re-occurring neighbor.

A node *performs* Neighbor Discovery by systematically receiving and processing the signals received during the DISC time slot and, possibly (through spatial multiplexing), on follow-on time slots.

HELLO burst reception is confirmed by the exchange of a short FOUND_YOU burst that includes the assignment of the code channel (i.e., set of orthogonal codes) to be used with in follow on SYNC bursts.

Neighbor Discovery ends with the exchange of orbital equation parameters between the nodes using the contention time slots of the frame.

Figure 14 illustrates the high-processing-gain elemental-signals (HELLO and FOUND_YOU bursts), and then the data messages exchanged between nodes performing new neighbor discovery.

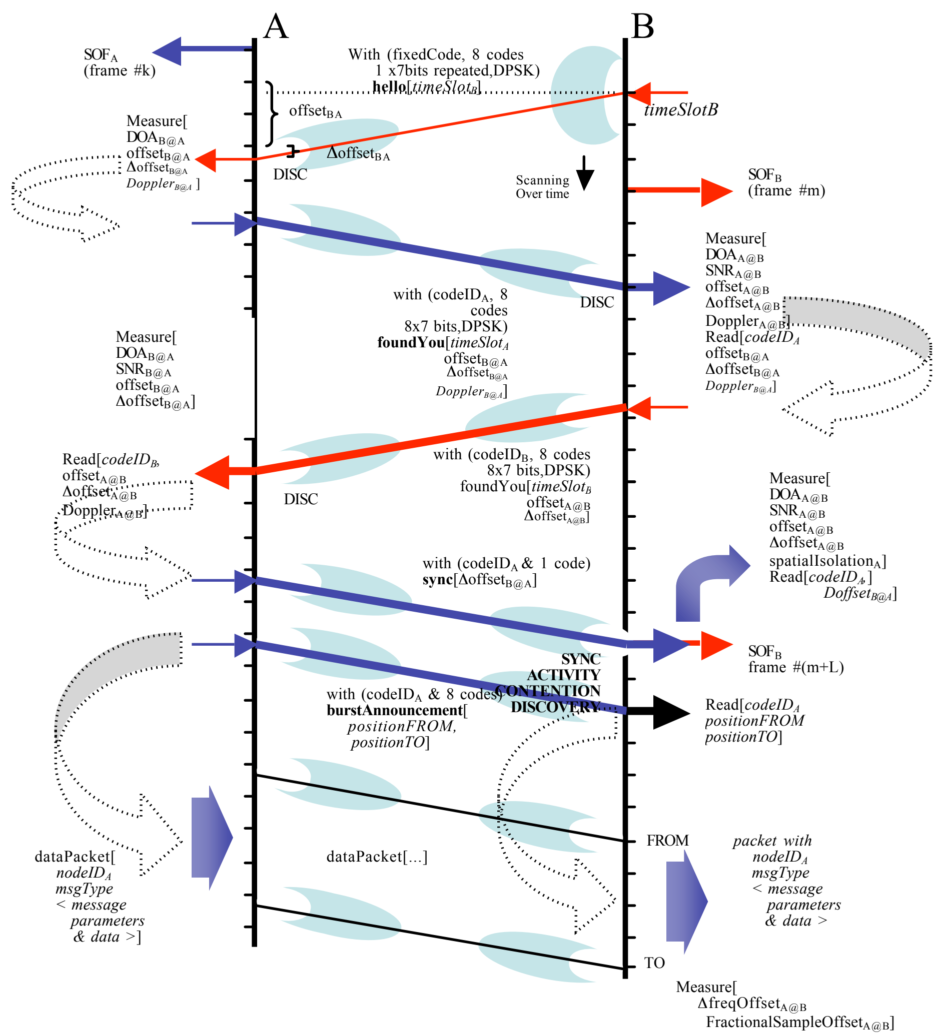

Fig. 14. Summary of Messages and Parameters for Neighbor Discovery

Also illustrated in the figure, although not discussed further in this paper, are the type of beams used (null-steered point to point or null-steered broadcast), the measurements performed at each step, the parameters included in subsequent messages, and the transition from initial HELLO and FOUND_YOU signals, to transmission/reception of time-slot synchronized SYNC bursts and, finally, at the end, to the transmission of Doppler-shift-compensated data packets.

Please note that Neighbor Discovery does not require the frames of the nodes performing "discovery" to be aligned in absolute time, nor the transmission of HELLO bursts to be the frequency synchronized with the receiving nodes: rough time and frequency offset are estimated as integral part of the neighbor discovery protocol, fine frame and time-slot synchronization is achieved with the exchange of SYNC bursts, and fine frequency offset measurements—for Doppler-shift compensation purposes—are performed as integral part of detecting exchanged data bursts.

B. Receiver-Directed Burst Synchronization

Burst transmission is performed synchronized with the frame and time-slots of a selected destination node (i.e., "receiver-directed"). In addition, since spacecraft cross-links are typically power-limited and transmissions to different neighbors are mutually asynchronous, transmission of time-overlapped bursts to distinct neighbors is not allowed. The multiple access protocol includes two synchronization components:

- A ***receiver-directed synchronization component***, used to control the burst transmission times, such that a burst transmitted to a target node is received synchronized with the time-slot boundaries of the target node (e.g., within ± 32 channel symbol times).
- A ***transmission scheduling component,*** used to enforce that transmissions to different neighbors do not overlap (in time) at the transmitting node.

Figure 15 illustrates the burst synchronization component.

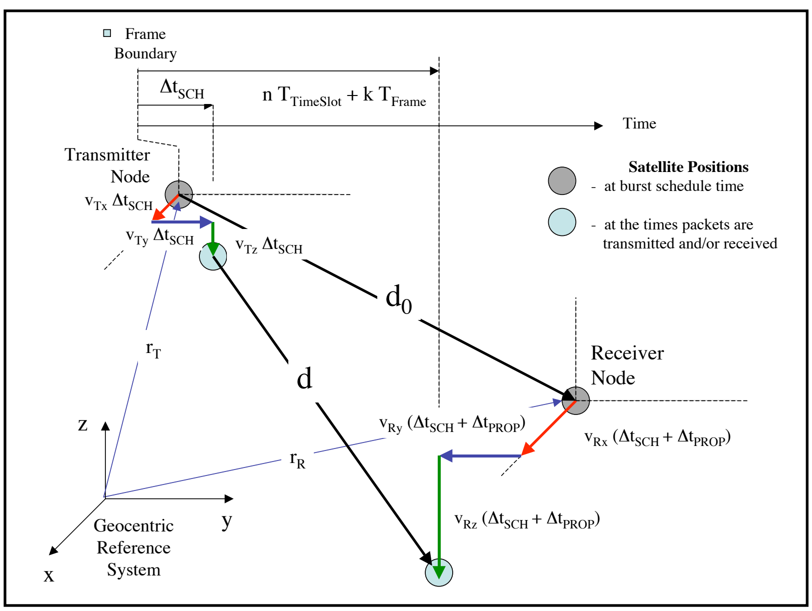

Fig. 15. Transmissions are performed such that they are received synchronized with the target node's local frame and time slots.

B.1. Receiver-Directed Burst Synchronization Algorithm

The main steps of the algorithm are summarized below:

1. The Transmitter Node receives a packet that is destined to a specific Receiver Node. The burst length is determined at this time by taking into account the effective symbol rate (calculated from the available link budget) and the modulation level (i.e., bits per symbol) calculated from the packet-required BER. Specifically, the burst length is minimized by selecting the best combination of effective symbol rate (i.e., number of codes) and modulation level (i.e., bits per symbol) that can be used to achieve the required Eb/No to close the link with the packet required BER. In this calculation we also take into consideration other TCeMA-specific encoding, modulating and formatting details such as: inclusion of a burst header (fixed length, BPSK modulation), bit-padding if necessary, and packet assembly/disassembly headers whenever the packet does not fit in one single TCeMA container.
1. Calculation of the actual transmission time is performed using as reference the start-of-frame (SOF) time in which the packet will actually be transmitted by the Transmitter Node. The coordinates of the Transmitter and Receiver nodes are calculated—for this reference time—using the orbital parameters exchanged during Neighbor Discovery.

The transmission time Δt_{SCH} and the propagation time are calculated next using the fact the $\Delta t_{SCH} + d/c = n\ T_{TimeSlot} + k\ T_{FRAME}$, where "n" is a selected time slot (e.g., time-slot #4), and "k" is a number of frames such that $k{*}T_{FRAME} \geq$ propagation time.

The detailed algorithm can be found in [9], and simulation results (in OPNET) for a constellation with 50 nodes, including ground stations and LEO, MEO and GEO satellites can be found in [10].

B.2. Burst Transmission Scheduling

The transmission-scheduling algorithm performs the following operations:

1. Check if the link can be closed using the coordinates of source and destination nodes;
1. Calculate the effective symbol rate and the modulation level to be used;
1. Calculate the burst length taking into account the burst format specifications (max container length in symbols, bits per symbol used, etc.);
1. Schedule the burst transmission time with respect to the SOF of its own/local next frame while assuming that the transmitted bursts should arrive at the destination node, in a pre-specified time slot of the earliest as possible frame;
1. Check for other previously scheduled bursts and "slide as required" the transmission time to avoid overlaps, while checking if the burst still "fits" in the destination-node frame;

1. At each sliding operation, re-compute the burst transmission time using the projected satellite positions while checking if the burst should be moved (or not) no the next frame.
1. If the burst does not "fit" in the frame, increment the value of "earliest destination-node frame" and go back to step #4.

Step #6 is required only if the satellites are moving very fast with respect with each other, such that the burst arrival-time at the destination node exceeds the maximum timing uncertainty for the system (e.g., ±64 channel symbol times). Simulation results show, even with dense LEO satellite constellations, that step #6 is rarely needed.

VIII. CONCLUSIONS

The development of the Hi-DSN project provided a unique opportunity to carefully address aspects of migrating approaches, technologies and protocols developed for terrestrial wireless *ad hoc* networking to space. More importantly, it allowed developing a deep understanding of technology features at the various protocol layers that are required for—and as such can be the enablers of—flexible multi-hop distributed spacecraft networks.

The paramount differences between a terrestrial wireless *ad hoc* network and a space-based multi-hop network are the magnitude of the distance between spacecraft combined with the rate in which such distances (and relative inter-satellite directions) vary over time, and the predictability of the spacecraft position over time. The use of high-gain antennas has to be engineered early on into the system design to enable "closing the link" and maintaining the overall network connected (i.e., a single "island"). In addition, the use of agile antenna beams has to be integrated with the MAC-layer protocol to enable the finding and the tracking-over-time of every in-range neighbor spacecraft. The orbital parameters, when available at each node, for all nodes in the constellation, greatly simplify the neighbor discovery and re-discovery processes. Below we provide a "wish list"—it can be interpreted as lessons learned—for engineering the architecture and for selecting technology features (at the various protocol layers) of future spacecraft networks that could adapt, scale and eventually become a long-lasting asset of the space based internetwork communications infrastructure of Figure 1:

- Support for cross-links with variable data rates is critical to forming and maintaining a multi-hop spacecraft network connected .
- Support for cross-link data rates varying over at least three orders-of-magnitude—as enabled by the TCeMA technology built into the modulation and encoding—is key to "closing the links" in constellations with "router-spacecraft" distributed over multiple-orbits. More importantly, the use of "conventional" rate adaptation techniques based on selectable BPSK/QPSK modulation, and selectable FEC rates, is not sufficient to handle the order-of-magnitude distance differences typical of the simplest multi-orbit spacecraft network.
- The use of a modulation and encoding technique such that a variable-rate cross-links can be achieved with a fixed-rate signaling over the channel—such as enabled by the TCeMA multi-code modulation described in this paper—is key for a node to be able to receive simultaneously from multiple neighbor spacecraft. More importantly, the use of a "conventional" variable-rate TDMA burst modem should not be considered as an option for such a multiplexing function, because receiving a low-rate TDMA signal (e.g., from a far away neighbor) would fully monopolize the use of "modem resources" at the receiving end, making difficult and costly to serve multiple simultaneous cross-links, as it is required to fully explore the spatial multiplexing capability inherent to distributed spacecraft networks.
- Support for digital beamforming in the receive direction enables the establishment of multiple simultaneous cross-links that "share" a single cross-link "burst modem" per spacecraft. This capability is relevant to the problem of designing "today" a system that will be deployed and operated ten years or more from now. More importantly, with the above capability the system designer and/or the mission planner would not have to "freeze" the number of cross-links per spacecraft nor pre-define how the constellation will look like when actually deployed.
- Support for digital beamforming in the transmit direction may not be required. Since the cross-links are typically power-limited, there is no need to provide support for multiple simultaneous transmit beams. Moreover, the required transmit beam agility (in azimuth and elevation) and null steering may be more cost-effectively implemented using "conventional" beamforming techniques (e.g., weights applied directly by the array elements).
- Our system designs [11-13], including simulation results [14-16] and laboratory prototype network experiments, showed that it is indeed possible to combine the advantages of multi-bit modulation, multi-code encoding and null-steered beamforming, and power-efficient transmission of the resulting signals.
- The systematic use of null steering toward non-target neighbor spacecraft—at both transmission and reception—enables forming space-based an *ad hoc* networks with non-interfering cross-links. This capability is extremely important because it enables the network to benefit fully from the spatial multiplexing and, more importantly, because it transforms (and simplifies) the link-level topology of a multi-orbit spacecraft network, from a "mesh" to a collection of disjoint "stars."
- Multi-code encoding using the BBN-developed TCeMA shift orthogonal codes has been shown to be up to the task of implementing cross-link data rates that can vary over at least three orders-of-magnitude.
- Provisioning of spatial multiplexing, integrated with a frame structure adapted to time-code multiplexing, enables "neighbor discovery" and, ultimately, network self-formation to happen with minimum or no interference with the "established" network.
- Time multiplexing has been shown to be the only practical means of achieving non-interfering cross-links among spacecraft that happen to be (or become) spatially aligned.

- A network self-formation strategy that relies solely on the knowledge of neighbor's location over time does not scale to networks that include endpoint nodes (e.g., aircraft, surface rovers and/or sensors).
- Support for reference clock sources (at each spacecraft) with "good" short and long term stability characteristics was key to facilitating "neighbor discovery" in situations in which the involved spacecraft have no a priori information of each other's coordinates and/or orbital parameters.

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REFERENCES

[1] K. Bhasin and J.L. Hayden, "Developing Architectures and Technologies for an Evolvable NASA Space Communication Infrastructure," *AIAA ICSSC, May 12, 2004.*

[2] New Vision for Space Exploration Program: Remarks by the President on U.S. Space Policy, NASA Headquarters, Washington, D.C., January 14, 2004.

[3] Workshop on Emerging Communications, Networks and Architectures Technologies for NASA Enterprises, NASA Glenn Research Center, August 7-9, 2001.

[4] Space Communications Project Access & Inter-spacecraft Networks Round Table, University of Maryland, May 14-15, 2003.

[5] K. Bhasin, "Integrated space communications Infrastructure: Network Buildout," unpublished.

[6] M. Bergamo, "Wireless Data Communications System," *U.S. Patent No. 6,104,708,* August 15, 2000.

[7] R. Preuss and M. Bergamo, "Data Communications System and Hybrid Time-Code Multiplexing," *U.S. Patent No. 6,590,889 B1*, July 8, 2003.

[8] M. Bergamo, "Constant Envelope Signal System and Method," patent pending (Filed on November 14, 2001 with the U.S. Patent and Trademark Office).

[9] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN: TCeMA Scheduling: Algorithm for Burst Transmission Time Calculation," Project Report, NASA Contract No. NAS3-01101, September 3, 2003.

[10] M. Bergamo and R. Hain, "High-Throughput Distributed Spacecraft Network (Hi-DSN: A Full Capability Simulation Study Using OPNET," Project Report, NASA Contract No. NAS3-01101, March 26, 2004.

[11] M. Bergamo and S. Ramanathan, "High-Throughput Distributed Spacecraft Network (Hi-DSN): System Design," Project Report, NASA Contract No. NAS3-01101, February 14, 2003.

[12] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN): Physical-Layer API Specification," Project Report, NASA Contract No. NAS3-01101, October 23, 2003.

[13] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN): MAC-Layer Design," Project Report, NASA Contract No. NAS3-01101, March 30, 2004.

[14] R. Hain and S. Ramanathan, "High-Throughput Distributed Spacecraft Network (Hi-DSN: Comparing Multiple Access Protocols for the Distributed Spacecraft Network: A Simulation Study using OPNET," Project Report, NASA Contract No. NAS3-01101, December 2002

[15] R. R. Hain, S. Ramanathan, M. Bergamo and T. M. Wallet, "Comparison of TCeMA and TDMA for Inter-satellite Communications using OPNET Simulation," OPNET Work 2003, August 25 – 29, 2003.

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